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Berger et al.

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(54) **POSITION-BASED REPLACEMENT POLICY FOR ADDRESS SYNONYM MANAGEMENT IN SHARED CACHES**

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G06F 12/08 (2016.01)

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CPC ***G06F 12/123*** (2013.01); ***G06F 12/084*** (2013.01); *G06F 2212/62* (2013.01); *G06F 2212/69* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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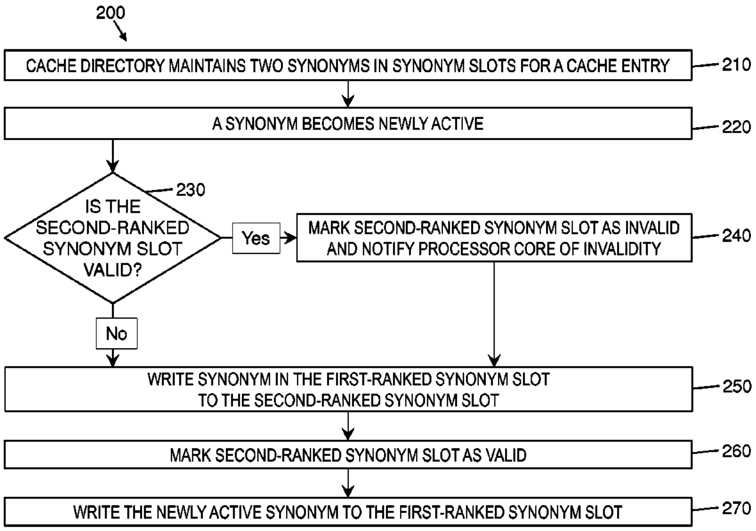
(57) **ABSTRACT**

A computer-implemented method includes receiving a request to access a cache entry in a shared cache. The request references a synonym for the cache entry. A cache directory of the shared cache includes, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry. The method includes, based on receiving the request, writing contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry, and writing the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

18 Claims, 3 Drawing Sheets


200
CACHE DIRECTORY MAINTAINS TWO SYNONYMS IN SYNONYM SLOTS FOR A CACHE ENTRY
210
A SYNONYM BECOMES NEWLY ACTIVE
220
IS THE SECOND-RANKED SYNONYM SLOT VALID?
230
Yes
MARK SECOND-RANKED SYNONYM SLOT AS INVALID AND NOTIFY PROCESSOR CORE OF INVALIDITY
240
No
WRITE SYNONYM IN THE FIRST-RANKED SYNONYM SLOT TO THE SECOND-RANKED SYNONYM SLOT
250
MARK SECOND-RANKED SYNONYM SLOT AS VALID
260
WRITE THE NEWLY ACTIVE SYNONYM TO THE FIRST-RANKED SYNONYM SLOT
270

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Garrett M. Drapala et al., pending U.S. Appl. No. 14/621,467, entitled "Dynamic Synchronous to Asynchronous Frequency Transitions in High-Performance Symmetric Multiprocessing," filed with the U.S. Patent and Trademark Office on Feb. 13, 2015.
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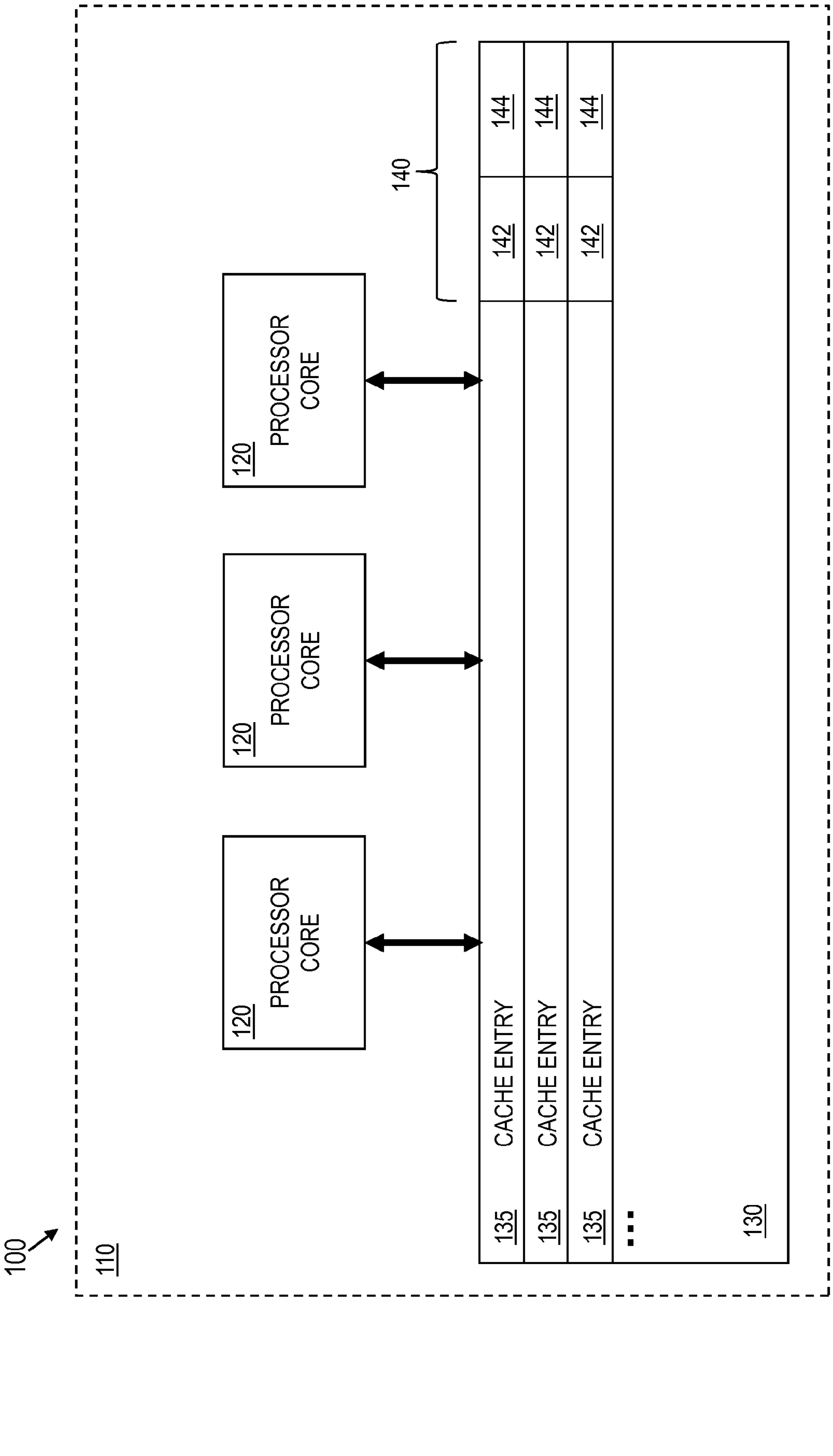
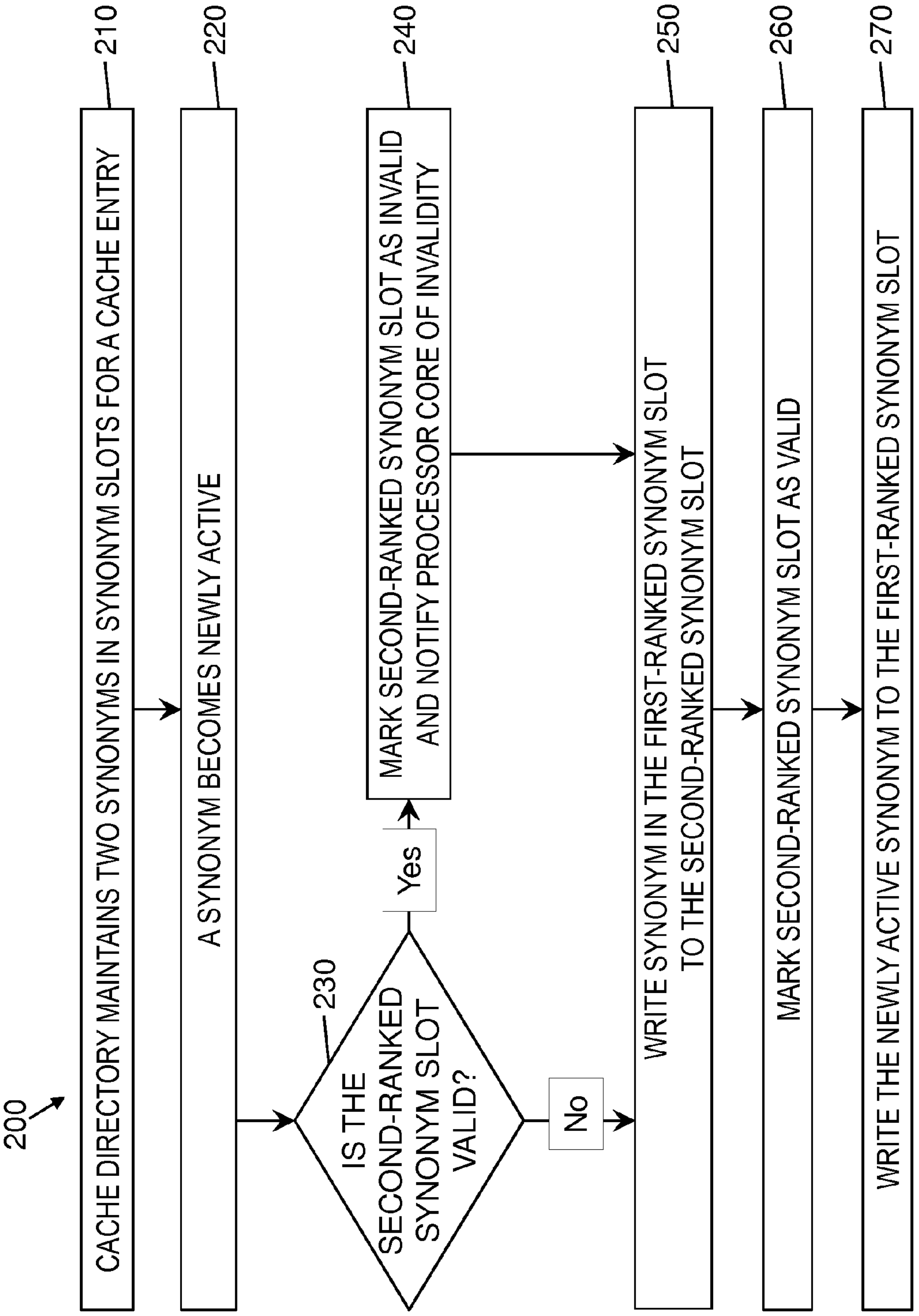

100
110
120 PROCESSOR CORE
120 PROCESSOR CORE
120 PROCESSOR CORE
140
142
144
142
144
142
144
135 CACHE ENTRY
135 CACHE ENTRY
135 CACHE ENTRY
...
130

Fig. 1


200
CACHE DIRECTORY MAINTAINS TWO SYNONYMS IN SYNONYM SLOTS FOR A CACHE ENTRY
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240
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WRITE SYNONYM IN THE FIRST-RANKED SYNONYM SLOT TO THE SECOND-RANKED SYNONYM SLOT
250
MARK SECOND-RANKED SYNONYM SLOT AS VALID
260
WRITE THE NEWLY ACTIVE SYNONYM TO THE FIRST-RANKED SYNONYM SLOT
270

Fig. 2

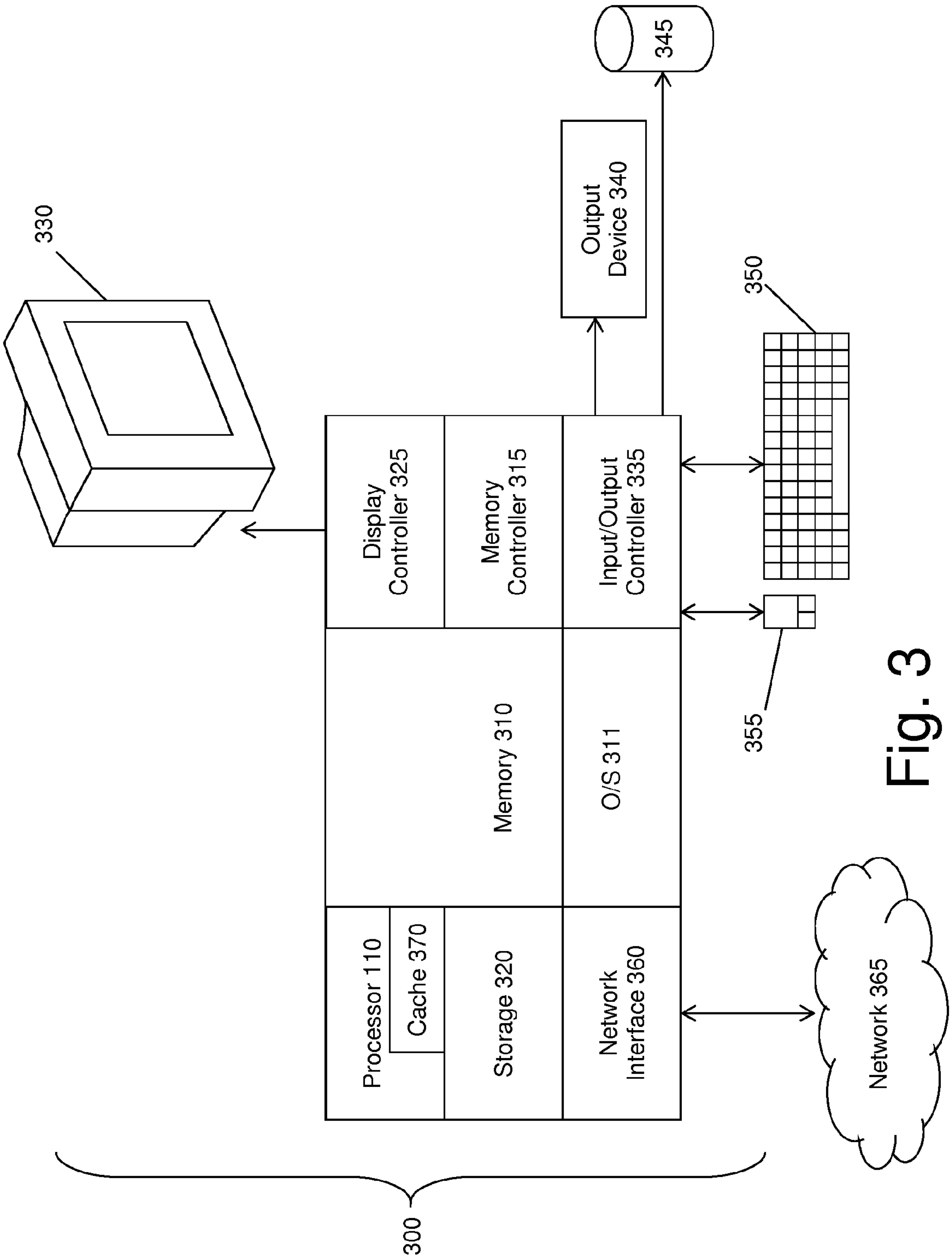
330
345
Output Device 340
350
Display Controller 325
Memory Controller 315
Input/Output Controller 335
Memory 310
O/S 311
355
Processor 110
Cache 370
Storage 320
Network Interface 360
Network 365
300

Fig. 3

POSITION-BASED REPLACEMENT POLICY FOR ADDRESS SYNONYM MANAGEMENT IN SHARED CACHES

BACKGROUND

Various embodiments of this disclosure relate to shared caches and, more particularly, to a position-based replacement policy for address synonym management in shared caches.

In a processor, each core may be associated with its own virtual memory, and virtual addresses in the virtual memory translate to physical addresses in the physical memory. Each core thus has access to its own translation lookaside buffer (TLB), which is specialized hardware private to its associated core. The TLB may handle translations back and forth between virtual and physical addresses for its associated core. Because there are multiple virtual address spaces, each physical address may map to multiple virtual addresses. Each set of virtual addresses that correspond to a common physical address is known as a set of synonyms. Various mechanisms exist for managing synonyms in a computer system.

SUMMARY

In one embodiment of this disclosure, a computer-implemented method includes receiving a request to access a cache entry in a shared cache. The request references a synonym for the cache entry. A cache directory of the shared cache includes, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry. The method includes, based on receiving the request, writing contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry, and writing the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

In another embodiment, a system includes one or more computer processors configured to receive a request to access a cache entry in a shared cache. The request references a synonym for the cache entry. A cache directory for the shared cache includes, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry. Based on receiving the request, the one or more processors are further configured to write contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry. Also based on receiving the request, the one or more processors are further configured to write the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

In yet another embodiment, a computer program product for implementing a least recently used replacement policy for synonyms in a cache directory of a shared cache includes a computer readable storage medium having program instructions embodied therewith. The program instructions are executable by a processor to cause the processor to perform a method. The method includes receiving a request to access a cache entry in a shared cache. The request references a synonym for the cache entry. A cache directory of the shared cache includes, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry. The method includes, based on receiving the request, writing contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry, and writing the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

Additional features and advantages are realized through the techniques of the present invention. Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. For a better understanding of the invention with the advantages and the features, refer to the description and to the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter which is regarded as the invention is particularly pointed out and distinctly claimed in the claims at the conclusion of the specification. The forgoing and other features, and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a block diagram of a processor using a synonym management system, according to some embodiments of this disclosure;

FIG. **2** is a flow diagram of a method for managing synonyms in a shared cache of a processor, according to some embodiments of this disclosure; and

FIG. **3** is a block diagram of a computing device for implementing some or all aspects of the synonym management system, according to some embodiments of this disclosure.

DETAILED DESCRIPTION

Synonym management systems, methods, and computer program products according to this disclosure can be used to manage synonyms (i.e., a set of virtual addresses corresponding to a common physical address) in level three (L3) cache or other shared cache.

A shared cache, such as the L3 cache, is shared across the cores of a processor having two or more cores. In the past, synonym translations between virtual addresses and physical addresses occurred strictly within the processor cores, for example, via the use of processor-specific translation lookaside buffers (TLBs), and the L3 cache handled only physical addresses. However, more recently, level two (L2) cache has become indexed by virtual addresses in some machines to improve access time. With this change, the L3 cache becomes responsible for managing synonyms, so the L3 directory was expanded to include up to two active synonyms. The two most recently used synonyms for each L3 cache entry are stored in a cache directory for the L3 cache, along with a validity bit for each synonym, indicating whether the corresponding stored synonym value is valid. A least recently used (LRU) replacement policy is used to determine which synonym to remove when a third synonym becomes active.

The conventional implementation of this policy requires further expansion of the L3 cache by one bit for each cache entry. The bit, referred to herein as the LRU bit, indicates which of the two synonyms being stored in the L3 cache was used least recently. When a third synonym becomes active, the processor looks at the LRU bit to determine which of the two stored synonyms was least recently used. The synonym deemed to be least recently used is then replaced with the newly active synonym, and the LRU bit is then set to indicate that the other, remaining synonym was least recently used. In this manner, the L3 cache can manage the two most recently used synonyms along with their associated cache entries.

Thus, with conventional synonym management, the L3 cache must maintain its entries, as well as an LRU bit for each cache entry indicating which synonym was least recently used and should therefore be replaced when another synonym becomes active. Thus, for an L3 cache that has 256,000 entries, 256,000 bits are required to maintain LRU bits for every entry. Embodiments of this disclosure may remove the need to maintain these additional bits and, as a result, may significantly reduce the hardware resources needed to manage synonyms.

FIG. **1** is a block diagram of a processor **110** using a synonym management system **100**, according to some embodiments of this disclosure. As shown, the processor **110** may include one or more cores **120** and a shared cache **130**, such as an L3 cache. A cache directory of the shared cache **130** may include two or more synonym slots **140** for each cache entry **135**, where each synonym slot may hold a single synonym for the associated cache entry **135** in the cache directory based on physical addresses. In conventional systems, the cache directory includes exactly two synonym slots **140** per cache entry **135**, but it will be understood that embodiments of this disclosure may be operative with shared caches whose directories maintain space for two or more synonyms per cache entry **135**. In contrast to conventional mechanisms of synonym management, the cache directory of the shared cache **130** need not maintain space for LRU bits.

According to some embodiments, the synonym slots **140** for each cache entry **135** may be ordered. A first-ranked synonym slot **142** may be filled by the synonym that was used most recently, while a second-ranked synonym slot **144** may be filled by the synonym used second most recently. If more than two synonym slots **140** are maintained, one of skill in the art will understand that each synonym slot **140** may be designated for a synonym based on how recently used that synonym is.

For example, a cache line for a particular physical address P includes two synonym slots, a first-ranked synonym slot **142** and a second-ranked synonym slot **144**. The first-ranked synonym slot **142** contains a synonym X, while the second-ranked synonym slot **144** contains a synonym Y. In this case, it is known that synonym X is the most recently used synonym for physical address P (i.e., physical address P was referred to by reference to synonym X more recently than any other synonym), because synonym X is stored in the first-ranked synonym slot **142**. It is also known that synonym Y is the second most recently used synonym for physical address P, because synonym Y is in the second-ranked synonym slot **144**.

When a request for a physical address is received referencing a synonym, where that synonym not currently stored in one of the synonym slots **140** of the corresponding cache entry **135**, that newly active synonym may displace one of the synonyms in the synonym slots **140** for the corresponding cache entry **135**. As a result, each of the synonyms in the synonym slots **140** may be demoted, i.e., moved down to a lower-ranked synonym slot **140**. More specifically, for example, when a synonym becomes newly active, the synonym in the first-ranked synonym slot **142** (i.e., the most recently used synonym) may be demoted to the second-ranked synonym slot **144**, while the synonym in the second-ranked synonym slot **144** (i.e., the second most recently used synonym) may also be demoted. In the case where exactly two synonym slots **140** are being used, demotion of the synonym in the second-ranked synonym slot **144** may remove this synonym from the synonym slots **140** altogether, such that this synonym is no longer stored in the cache directory. More generally, the lowest ranked (i.e., least recently used) synonym stored in the synonym slots **140** may be demoted out of the cache directory when a newly active synonym is added to the synonym slots **140**. The newly active synonym may be written to the first-ranked synonym slot **142** (i.e., the synonym slot **140** for the most recently used synonym).

As mentioned above, each synonym slot **140** may have an associated validity bit in the cache directory, indicating whether the corresponding value in the synonym slot **140** is a valid synonym. The first time a cache access request is received for a specific physical address, which is when the address will be first loaded into the shared cache **130**, there will be only a single valid synonym. This valid synonym may be written into the first-ranked synonym slot **142** for the cache line, and the validity bit for first-ranked synonym slot **142** may be turned on (e.g., marked as valid, set to a value of 1 or TRUE). Because only a single synonym has been used, the validity bit for the second-ranked synonym slot **144** may remain off. When a second synonym becomes active, the contents of the first-ranked synonym slot **142** may be written to the second-ranked synonym slot **144**, and the second-ranked synonym slot's corresponding validity bit may be turned on. The newly active synonym may be written to the first-ranked synonym slot **142**.

For each later request related to the same physical address, there may be period of time during which the synonym in the second-ranked synonym slot **144** (or the lowest-ranked synonym slot **140**, if more than two synonym slots **140** are being used) becomes invalid. For instance, when a third synonym becomes active, the synonym in the second-ranked synonym slot **144** may now be invalid because only two synonyms are being maintained in the cache directory. Thus, the validity bit corresponding to the second-ranked synonym slot **144** may be turned off (e.g., marked as invalid, set to a value of 0 or FALSE), until the synonym in the first-ranked synonym slot **142** is moved to the second-ranked synonym slot **144**. The one or more processor cores **120** associated with the now-invalid synonym may be notified that the synonym is no longer active. Once the move occurs, the validity bit may be turned back on. There may be no need to change the validity bit of the first-ranked synonym slot **142** after it is initially turned on, because the synonym maintained in the first-ranked synonym slot **142** is being moved to the second-ranked synonym slot **144** and remaining in the cache directory as an active synonym.

Returning to the above example, in which synonym X and synonym Y are stored respectively in the first-ranked and second-ranked synonym slots **142** and **144** for physical address P, suppose a synonym Z becomes newly active for physical address P. In this case, synonym P is now the most recently used synonym for physical address P and may thus be stored in the first-ranked synonym slot **142**. The validity bit for the second-ranked synonym slot **144** is turned off, responsive to the newly active synonym. The current contents of the first-ranked synonym slot **142**, specifically synonym X, are written to the second-ranked synonym slot **144**. The validity bit for the second-ranked synonym slot **144** is then be turned back on. Synonym X is thus demoted from the first-ranked synonym slot **142** to the second-ranked synonym slot **144**. Synonym Z is written is written to the first-ranked synonym slot **142**, because it is the most recently used synonym for physical address P. In this example, only two synonym slots **140** are being used, so synonym Y is demoted from all synonym slots **140**. The processor cores **120** associated with synonym Y is notified that synonym Y is no longer referenced in the shared cache **130**.

In some cases, a request for a physical address may refer to a synonym already stored in a synonym slot of the cache directory. In some embodiments, if the request refers to the synonym in the first-ranked synonym slot, the values stored in the first-ranked and second-ranked synonym slots **140** may remain unchanged. In the case where the request refers to the synonym in the second-ranked synonym slot **144**, the synonyms in the first-ranked and second-ranked synonym slots **142** and **144** may be swapped. In some further embodiments, this swap may be implemented in the same manner as other synonym replacements; for example, the value in the second-ranked synonym slot **144** may be overwritten with the value in first-ranked synonym slot **142**, and the synonym referenced in the request may then be written to the first-ranked synonym slot **142**.

Thus, the position of a synonym within the synonym slots **140** of the cache directory may determine how recently a synonym was used, and may therefore be used to implement an LRU replacement policy for synonyms. According to some embodiments, no LRU bit need be maintained because the positions of the synonyms within the synonym slots **140** may serve the purpose of ordering the synonyms based on recent use.

FIG. **2** is a flow diagram of a method **200** for managing synonyms in a shared cache **130** of a processor, according to some embodiments of this disclosure. As shown, at block **210**, a cache directory of the shared cache **130** may maintain two synonyms in the synonym slots **140**, a first-ranked synonym slot **142** and a second-ranked synonym slot **144**, of a cache entry **135**. The first-ranked synonym slot **142** may hold the most recently used synonym for the cache entry **135**, while the second-ranked synonym slot **144** may hold the second most recently used synonym. At block **220**, a synonym may become newly active. At decision block **230**, the processor **110** may determine whether the second-ranked synonym slot **144** is valid, i.e., whether the corresponding validity bit is turned on. If the second-ranked synonym slot **144** is not valid, then the method **200** may go to block **250**. On the other hand, if the second-ranked synonym slot **144** is valid, then at block **240**, the second-ranked synonym slot **144** may be marked as invalid, and the associated processor cores **120** may be notified. The method may then go to block **250**. At block **250**, the processor **110** may write the synonym in the first-ranked synonym slot **142** to the second-ranked synonym slot **144**. At block **260**, the second-ranked synonym slot **144** may be marked as valid, indicating the synonym in that position is valid. At block **270**, the processor may write the newly active synonym to the first-ranked synonym slot **142**. Thus, the newly active synonym may take the position of the most recently used synonym, while the previous most recently used synonym takes the position of the second most recently used synonym. The least recently used synonym that was stored in the synonym slots **140** prior to the method **200** may be overwritten and thus removed from the synonym slots **140** and from the cache directory.

FIG. **3** illustrates a block diagram of a computer system **300** for use in implementing a synonym management system or method according to some embodiments. The synonym management systems and methods described herein may be implemented in hardware, software (e.g., firmware), or a combination thereof. In some embodiments, the methods described may be implemented, at least in part, in hardware and may be part of the microprocessor of a special or general-purpose computer system **300**, such as a personal computer, workstation, minicomputer, or mainframe computer.

In some embodiments, as shown in FIG. **3**, the computer system **300** includes a processor **110**, physical memory **310** coupled to a memory controller **315**, and one or more input devices **345** and/or output devices **340**, such as peripherals, that are communicatively coupled via a local I/O controller **335**. These devices **340** and **345** may include, for example, a printer, a scanner, a microphone, and the like. Input devices such as a conventional keyboard **350** and mouse **355** may be coupled to the I/O controller **335**. The I/O controller **335** may be, for example, one or more buses or other wired or wireless connections, as are known in the art. The I/O controller **335** may have additional elements, which are omitted for simplicity, such as controllers, buffers (caches), drivers, repeaters, and receivers, to enable communications.

The I/O devices **340**, **345** may further include devices that communicate both inputs and outputs, for instance disk and tape storage, a network interface card (NIC) or modulator/demodulator (for accessing other files, devices, systems, or a network), a radio frequency (RF) or other transceiver, a telephonic interface, a bridge, a router, and the like.

The processor **110** is a hardware device for executing hardware instructions or software, particularly those stored in the physical memory **310**. The processor **110** may be a custom made or commercially available processor, a central processing unit (CPU), an auxiliary processor among several processors associated with the computer system **300**, a semiconductor based microprocessor (in the form of a microchip or chip set), a macroprocessor, or other device for executing instructions. The processor **110** includes a cache **370**, which may include, but is not limited to, an instruction cache to speed up executable instruction fetch, a data cache to speed up data fetch and store, and a translation lookaside buffer (TLB) used to speed up virtual-to-physical address translation for both executable instructions and data. The cache **370** may be organized as a hierarchy of more cache levels (L1, L2, etc.). One of such cache levels may be the shared cache **130**, which may maintain the synonym slots **140** in its cache directory as discussed above.

The memory **310** may include one or combinations of volatile memory elements (e.g., random access memory, RAM, such as DRAM, SRAM, SDRAM, etc.) and nonvolatile memory elements (e.g., ROM, erasable programmable read only memory (EPROM), electronically erasable programmable read only memory (EEPROM), programmable read only memory (PROM), tape, compact disc read only memory (CD-ROM), disk, diskette, cartridge, cassette or the like, etc.). Moreover, the memory **310** may incorporate electronic, magnetic, optical, or other types of storage media. Note that the memory **310** may have a distributed architecture, where various components are situated remote from one another but may be accessed by the processor **110**.

The instructions in memory **310** may include one or more separate programs, each of which comprises an ordered listing of executable instructions for implementing logical functions. In the example of FIG. **3**, the instructions in the memory **310** include a suitable operating system (OS) **311**. The operating system **311** essentially may control the execution of other computer programs and provides scheduling, input-output control, file and data management, memory management, and communication control and related services.

Additional data, including, for example, instructions for the processor **110** or other retrievable information, may be stored in storage **320**, which may be a storage device such as a hard disk drive or solid state drive.

The computer system **300** may further include a display controller **325** coupled to a display **330**. In some embodiments, the computer system **300** may further include a network interface **360** for coupling to a network **365**. The network **365** may be an IP-based network for communication between the computer system **300** and an external server, client and the like via a broadband connection. The network **365** transmits and receives data between the computer system **300** and external systems. In some embodiments, the network **365** may be a managed IP network administered by a service provider. The network **365** may be implemented in a wireless fashion, e.g., using wireless protocols and technologies, such as WiFi, WiMax, etc. The network **365** may also be a packet-switched network such as a local area network, wide area network, metropolitan area network, the Internet, or other similar type of network environment. The network **365** may be a fixed wireless network, a wireless local area network (LAN), a wireless wide area network (WAN) a personal area network (PAN), a virtual private network (VPN), intranet or other suitable network system and may include equipment for receiving and transmitting signals.

Synonym management systems and methods according to this disclosure may be embodied, in whole or in part, in computer program products or in computer systems **300**, such as that illustrated in FIG. **3**.

Technical effects and benefits of some embodiments include a least recently used replacement policy that need not require separate logic or circuits to keep track of which synonyms are the oldest. With a large cache, which can have over 256,000 entries, independent circuits for maintaining an LRU policy for synonym replacement would consume significant resources. Embodiments of this disclosure may avoid the consumption of such resources for this purpose.

The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms "comprises" and/or "comprising," when used in this specification, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

The corresponding structures, materials, acts, and equivalents of all means or step plus function elements in the claims below are intended to include any structure, material, or act for performing the function in combination with other claimed elements as specifically claimed. The description of the present invention has been presented for purposes of illustration and description, but is not intended to be exhaustive or limited to the invention in the form disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the invention. The embodiments were chosen and described in order to best explain the principles of the invention and the practical application, and to enable others of ordinary skill in the art to understand the invention for various embodiments with various modifications as are suited to the particular use contemplated.

The present invention may be a system, a method, and/or a computer program product. The computer program product may include a computer readable storage medium (or media) having computer readable program instructions thereon for causing a processor to carry out aspects of the present invention.

The computer readable storage medium can be a tangible device that can retain and store instructions for use by an instruction execution device. The computer readable storage medium may be, for example, but is not limited to, an electronic storage device, a magnetic storage device, an optical storage device, an electromagnetic storage device, a semiconductor storage device, or any suitable combination of the foregoing. A non-exhaustive list of more specific examples of the computer readable storage medium includes the following: a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a static random access memory (SRAM), a portable compact disc read-only memory (CD-ROM), a digital versatile disk (DVD), a memory stick, a floppy disk, a mechanically encoded device such as punch-cards or raised structures in a groove having instructions recorded thereon, and any suitable combination of the foregoing. A computer readable storage medium, as used herein, is not to be construed as being transitory signals per se, such as radio waves or other freely propagating electromagnetic waves, electromagnetic waves propagating through a waveguide or other transmission media (e.g., light pulses passing through a fiber-optic cable), or electrical signals transmitted through a wire.

Computer readable program instructions described herein can be downloaded to respective computing/processing devices from a computer readable storage medium or to an external computer or external storage device via a network, for example, the Internet, a local area network, a wide area network and/or a wireless network. The network may comprise copper transmission cables, optical transmission fibers, wireless transmission, routers, firewalls, switches, gateway computers and/or edge servers. A network adapter card or network interface in each computing/processing device receives computer readable program instructions from the network and forwards the computer readable program instructions for storage in a computer readable storage medium within the respective computing/processing device.

Computer readable program instructions for carrying out operations of the present invention may be assembler instructions, instruction-set-architecture (ISA) instructions, machine instructions, machine dependent instructions, microcode, firmware instructions, state-setting data, or either source code or object code written in any combination of one or more programming languages, including an object oriented programming language such as Java, Smalltalk, C++ or the like, and conventional procedural programming languages, such as the "C" programming language or similar programming languages. The computer readable program instructions may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider). In some embodiments, electronic circuitry including, for example, programmable logic circuitry, field-programmable gate arrays (FPGA), or programmable logic arrays (PLA) may execute the computer readable program instructions by utilizing state information of the computer readable program instructions to personalize the electronic circuitry, in order to perform aspects of the present invention.

Aspects of the present invention are described herein with reference to flowchart illustrations and/or block diagrams of methods, apparatus (systems), and computer program products according to embodiments of the invention. It will be understood that each block of the flowchart illustrations and/or block diagrams, and combinations of blocks in the flowchart illustrations and/or block diagrams, can be implemented by computer readable program instructions.

These computer readable program instructions may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks. These computer readable program instructions may also be stored in a computer readable storage medium that can direct a computer, a programmable data processing apparatus, and/or other devices to function in a particular manner, such that the computer readable storage medium having instructions stored therein comprises an article of manufacture including instructions which implement aspects of the function/act specified in the flowchart and/or block diagram block or blocks.

The computer readable program instructions may also be loaded onto a computer, other programmable data processing apparatus, or other device to cause a series of operational steps to be performed on the computer, other programmable apparatus or other device to produce a computer implemented process, such that the instructions which execute on the computer, other programmable apparatus, or other device implement the functions/acts specified in the flowchart and/or block diagram block or blocks.

The flowchart and block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of systems, methods, and computer program products according to various embodiments of the present invention. In this regard, each block in the flowchart or block diagrams may represent a module, segment, or portion of instructions, which comprises one or more executable instructions for implementing the specified logical function(s). In some alternative implementations, the functions noted in the block may occur out of the order noted in the figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts or carry out combinations of special purpose hardware and computer instructions.

The descriptions of the various embodiments of the present invention have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

What is claimed is:

1. A computer-implemented method, comprising:

receiving a request to access a cache entry in a shared cache, the request referencing a synonym for the cache entry, a cache directory of the shared cache comprising, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry; and

based on receiving the request:

writing contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry; and

writing the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

2. The method of claim **1**, wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes an other synonym from the second-ranked synonym slot for the cache entry.

3. The method of claim **2**, wherein the cache directory comprises no more than two synonym slots for the cache entry, and wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes the other synonym from the cache directory.

4. The method of claim **1**, wherein the cache directory comprises two or more synonym slots for each cache entry, and wherein a position of each synonym within the synonym slots is based on recent use relative to one or more other synonyms in the synonym slots.

5. The method of claim **4**, wherein the cache directory is absent circuitry, other than the two or more synonym slots, for indicating which synonym was most recently used.

6. The method of claim **1**, further comprising:

receiving an other request for an other cache entry, wherein the other request references an other synonym;

determining that the other synonym matches a synonym stored in the second-ranked synonym slot of the other cache entry; and

swapping the synonyms in the first-ranked synonym slot and the second-ranked synonym slot of the other cache entry, responsive to determining that the other synonym matches the synonym stored in the second-ranked synonym slot of the other cache entry.

7. A system comprising:

one or more computer processors configured to:

receive a request to access a cache entry in a shared cache, the request referencing a synonym for the cache entry, a cache directory of the shared cache comprising, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry; and

based on receiving the request:

write contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry; and

write the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

8. The system of claim **7**, wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes an other synonym from the second-ranked synonym slot for the cache entry.

9. The system of claim **8**, wherein the cache directory comprises no more than two synonym slots for the cache entry, and wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes the other synonym from the cache directory.

10. The system of claim **7**, wherein the cache directory comprises two or more synonym slots for each cache entry, and wherein a position of each synonym within the synonym slots is based on recent use relative to one or more other synonyms in the synonym slots.

11. The system of claim **10**, wherein the cache directory is absent circuitry, other than the two or more synonym slots, for indicating which synonym was most recently used.

12. The system of claim **7**, the one or more processors further configured to:

receive an other request for an other cache entry, wherein the other request references an other synonym;

determine that the other synonym matches a synonym stored in the second-ranked synonym slot of the other cache entry; and

swap the synonyms in the first-ranked synonym slot and the second-ranked synonym slot of the other cache entry, responsive to determining that the other synonym matches the synonym stored in the second-ranked synonym slot of the other cache entry.

13. A computer program product for implementing a least recently used replacement policy for synonyms in a cache directory of a shared cache, the computer program product comprising a computer readable storage medium having program instructions embodied therewith, the program instructions executable by a processor to cause the processor to perform a method comprising:

receiving a request to access a cache entry in a shared cache, the request referencing a synonym for the cache entry, a cache directory of the shared cache comprising, for each cache entry of the shared cache, a first-ranked synonym slot for storing a most recently used synonym for the cache entry and a second-ranked synonym slot for storing a second most recently used synonym for the cache entry; and

based on receiving the request:

writing contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry; and

writing the synonym referenced in the request to the first-ranked synonym slot for the cache entry.

14. The computer program product of claim **13**, wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes an other synonym from the second-ranked synonym slot for the cache entry.

15. The computer program product of claim **14**, wherein the cache directory comprises no more than two synonym slots for the cache entry, and wherein writing the contents of the first-ranked synonym slot for the cache entry to the second-ranked synonym slot for the cache entry demotes the other synonym from the cache directory.

16. The computer program product of claim **13**, wherein the cache directory comprises two or more synonym slots for each cache entry, and wherein a position of each synonym within the synonym slots is based on recent use relative to one or more other synonyms in the synonym slots.

17. The computer program product of claim **16**, wherein the cache directory is absent circuitry, other than the two or more synonym slots, for indicating which synonym was most recently used.

18. The computer program product of claim **13**, the method further comprising:

receiving an other request for an other cache entry, wherein the other request references an other synonym;

determining that the other synonym matches a synonym stored in the second-ranked synonym slot of the other cache entry; and

swapping the synonyms in the first-ranked synonym slot and the second-ranked synonym slot of the other cache entry, responsive to determining that the other synonym matches the synonym stored in the second-ranked synonym slot of the other cache entry.

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